Basic Linac Microwave

In 2.7 x 10^9 μsec

Part III

Lecture Presented to OPS Group

~~May 24, 2000~~

~~May 31, 2000~~

June 7, 2000

A. Nassiri, RF Group

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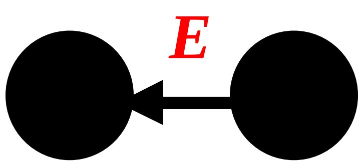
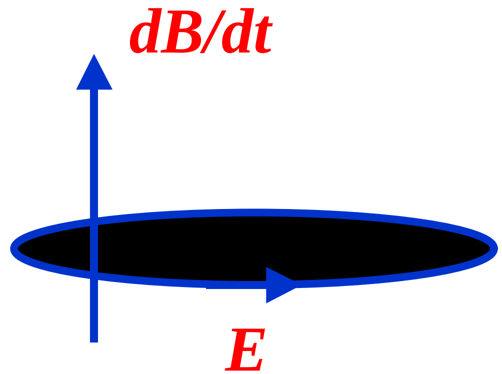
How to Accelerate?

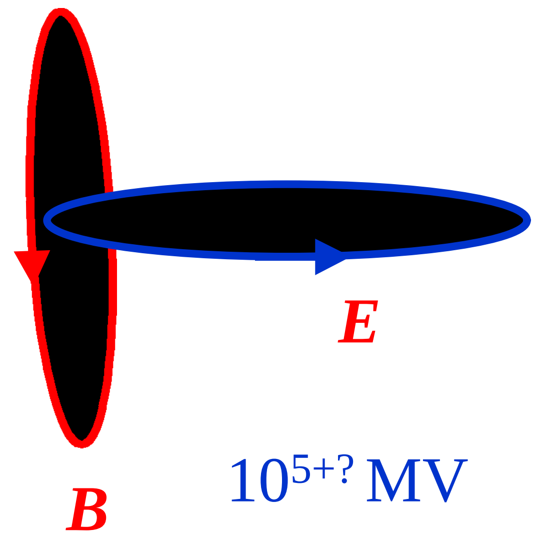
$$\frac{de}{dt} = q\vec{v} \bullet \vec{E}$$



10^0 MV

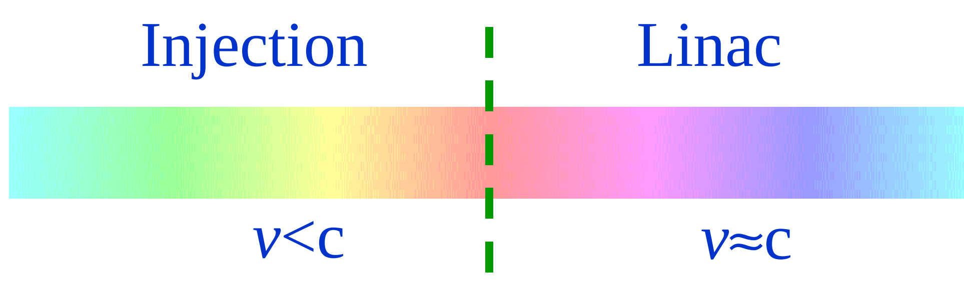


10^2 MV



$10^{5+?}$ MV

$$\Delta e = \int dt E_0 \cos(w - kv)t$$



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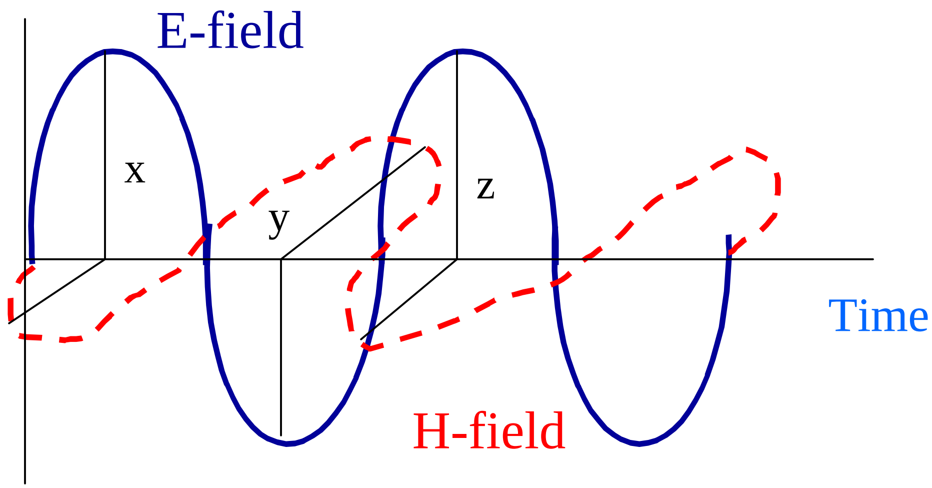
$$f_r = \frac{1}{2p\sqrt{LC}}$$

$$c = \lambda/\mathrm{T} = \lambda \times 1/\mathrm{T} = f\,\lambda$$

Propagation Fields



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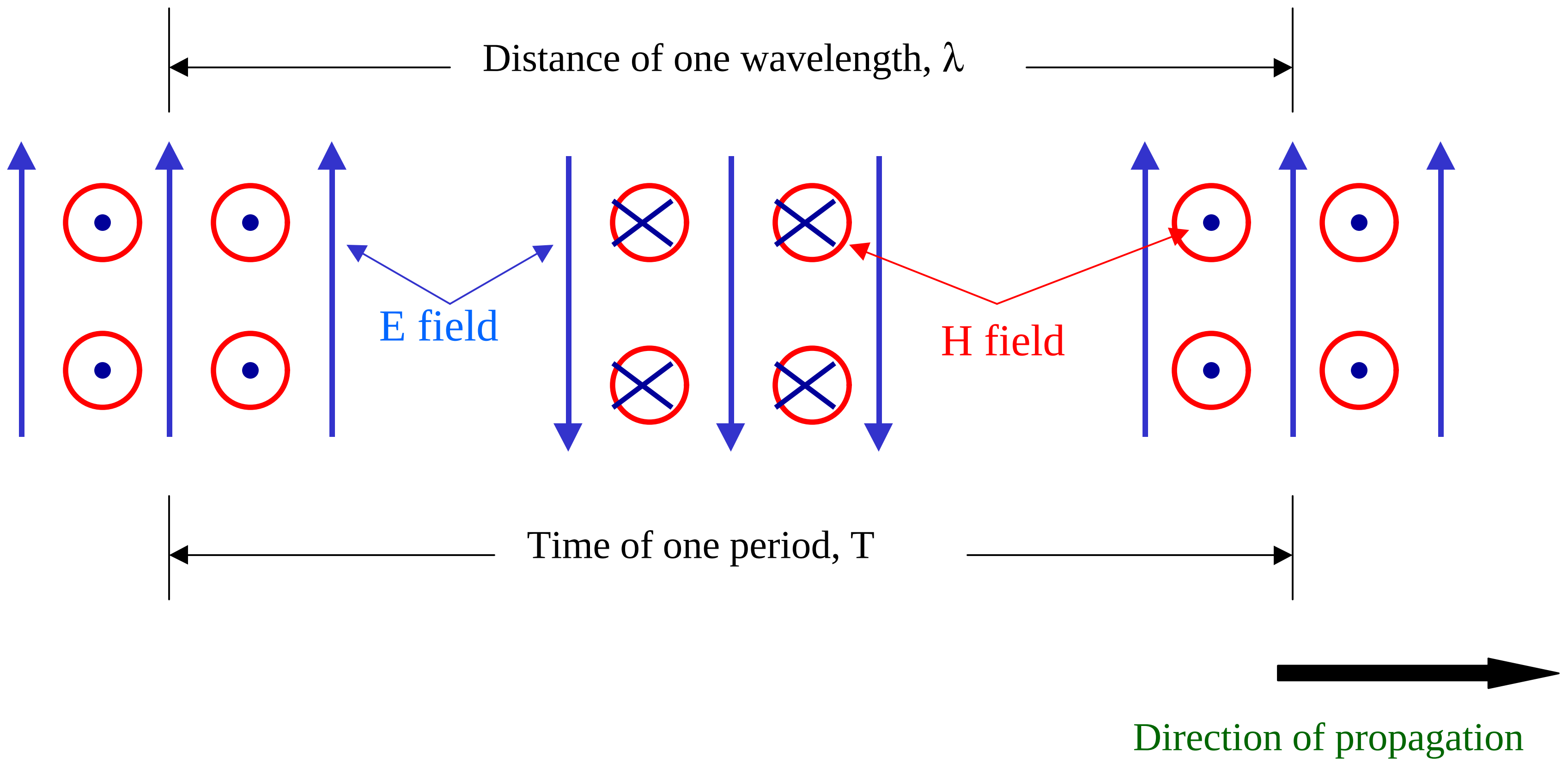

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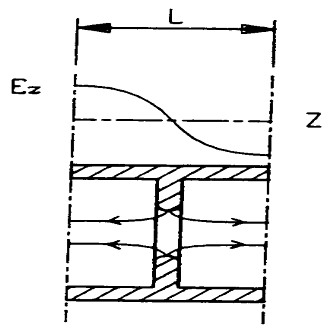
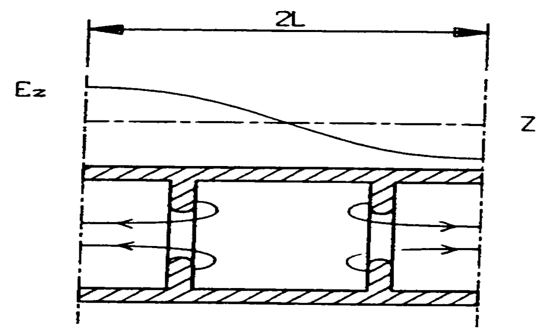
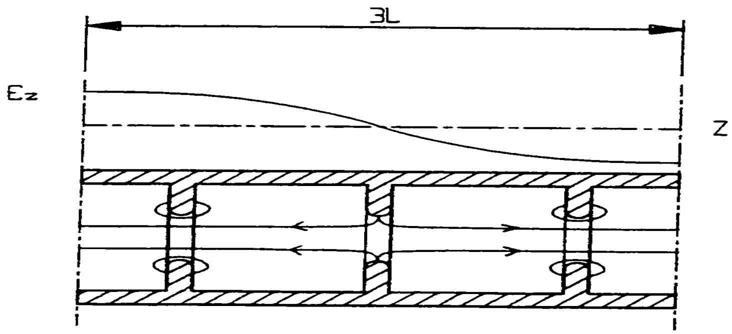


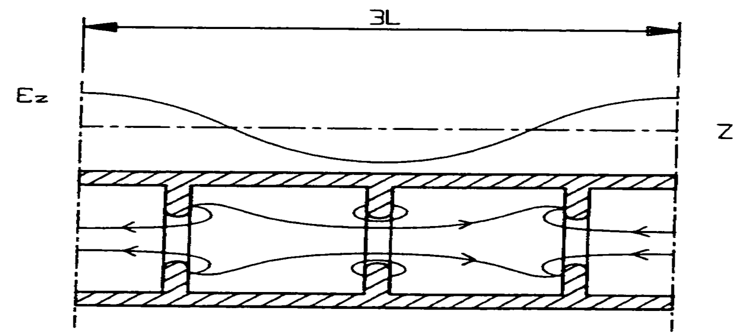
a) $\beta L = \pi$; $f_\pi = 2.965$ GHz



b) $\beta L = \frac{\pi}{2}$; $f_{\pi/2} = 2.947$ GHz



c) $\beta L = \frac{\pi}{3}$; $f_{\pi/3} = 2.938$ GHz



d) $\beta L = \frac{2}{3}\pi$; $f_{2/3\,\pi} = 2.957$ GHz

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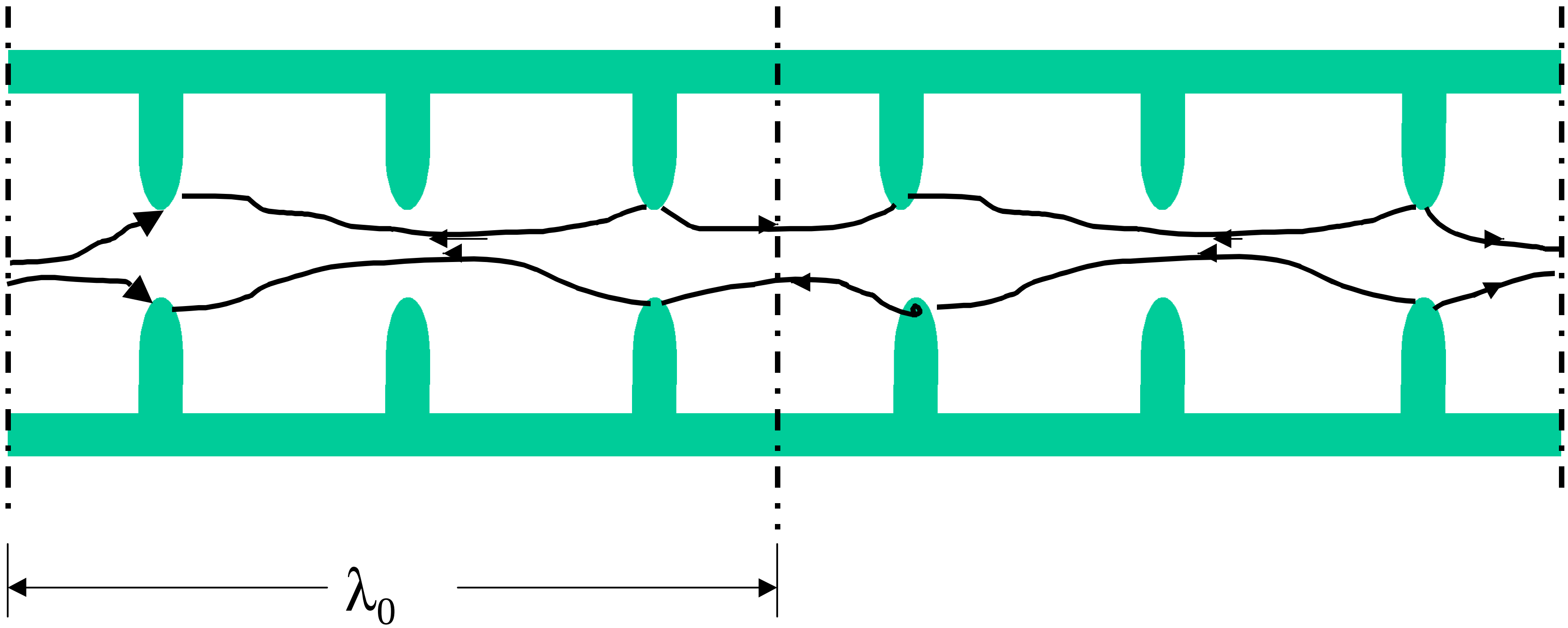
Accelerating Structure



2π/3 phase shift per cell

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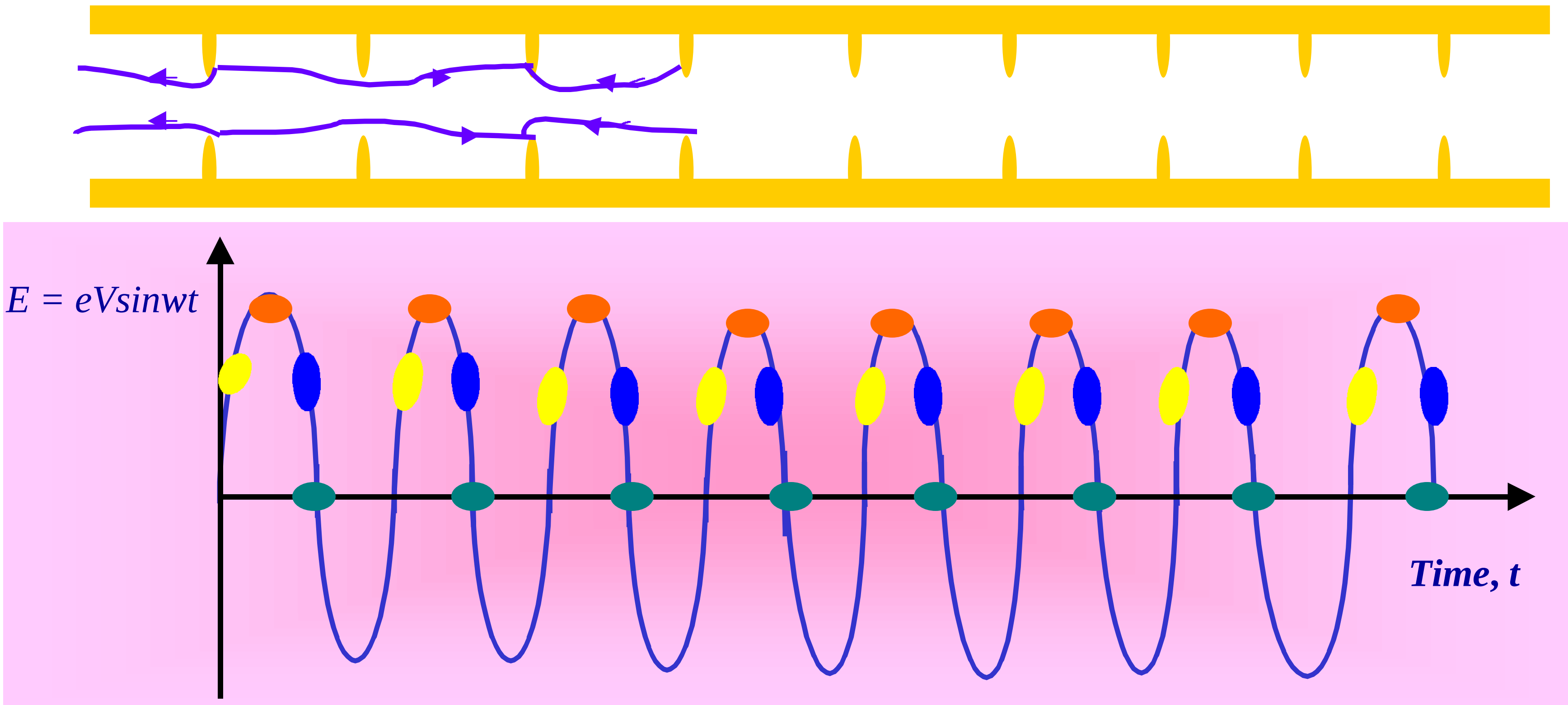

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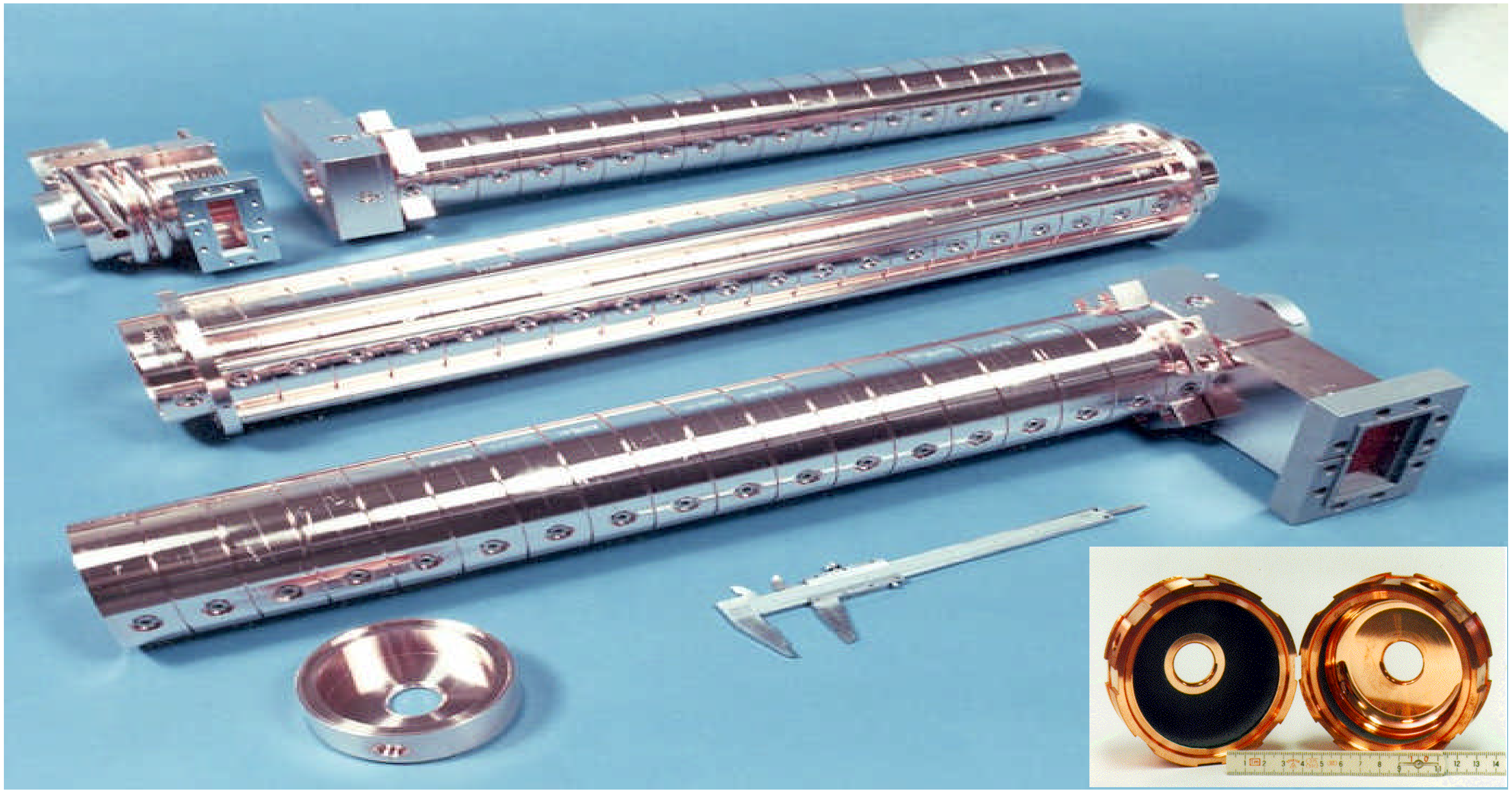

Disk-Loaded Constant Gradient S-Band Structure

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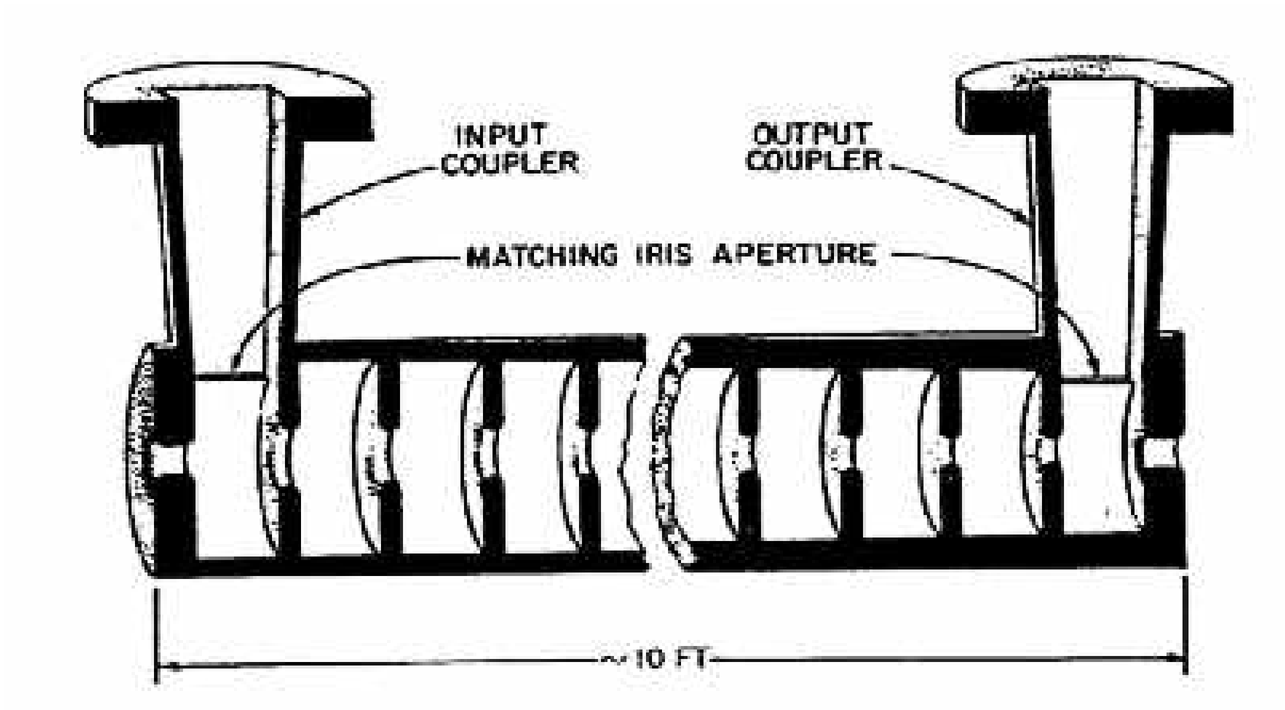

S-band disk-loaded accelerating structure

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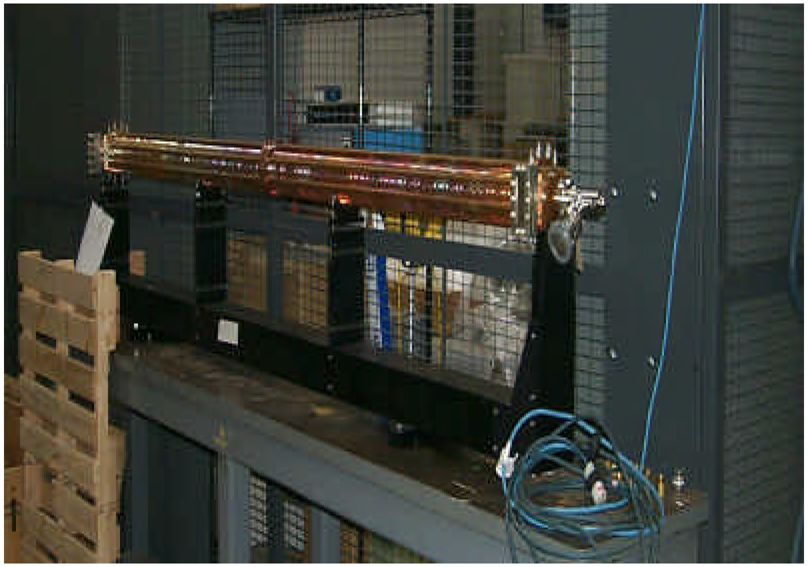
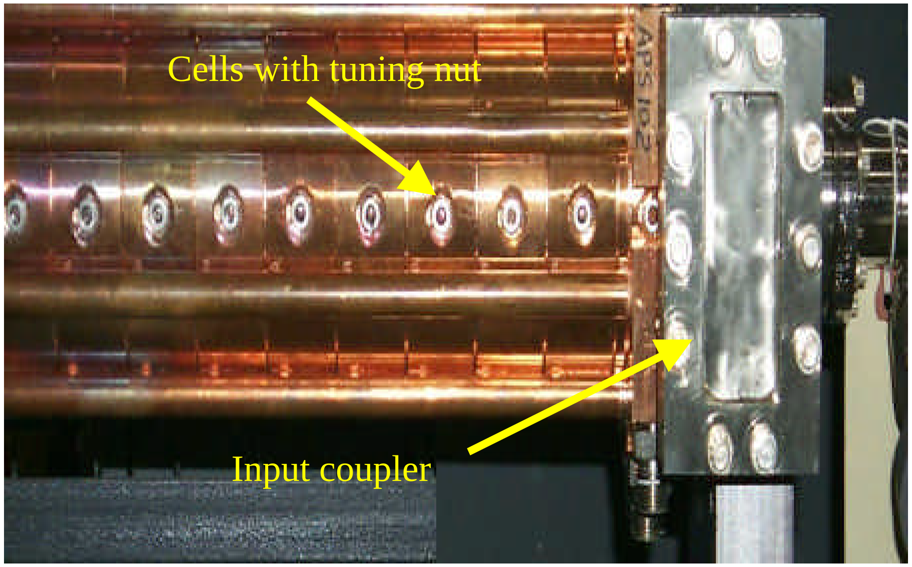


3-meters S-band Structure



Input coupling cell

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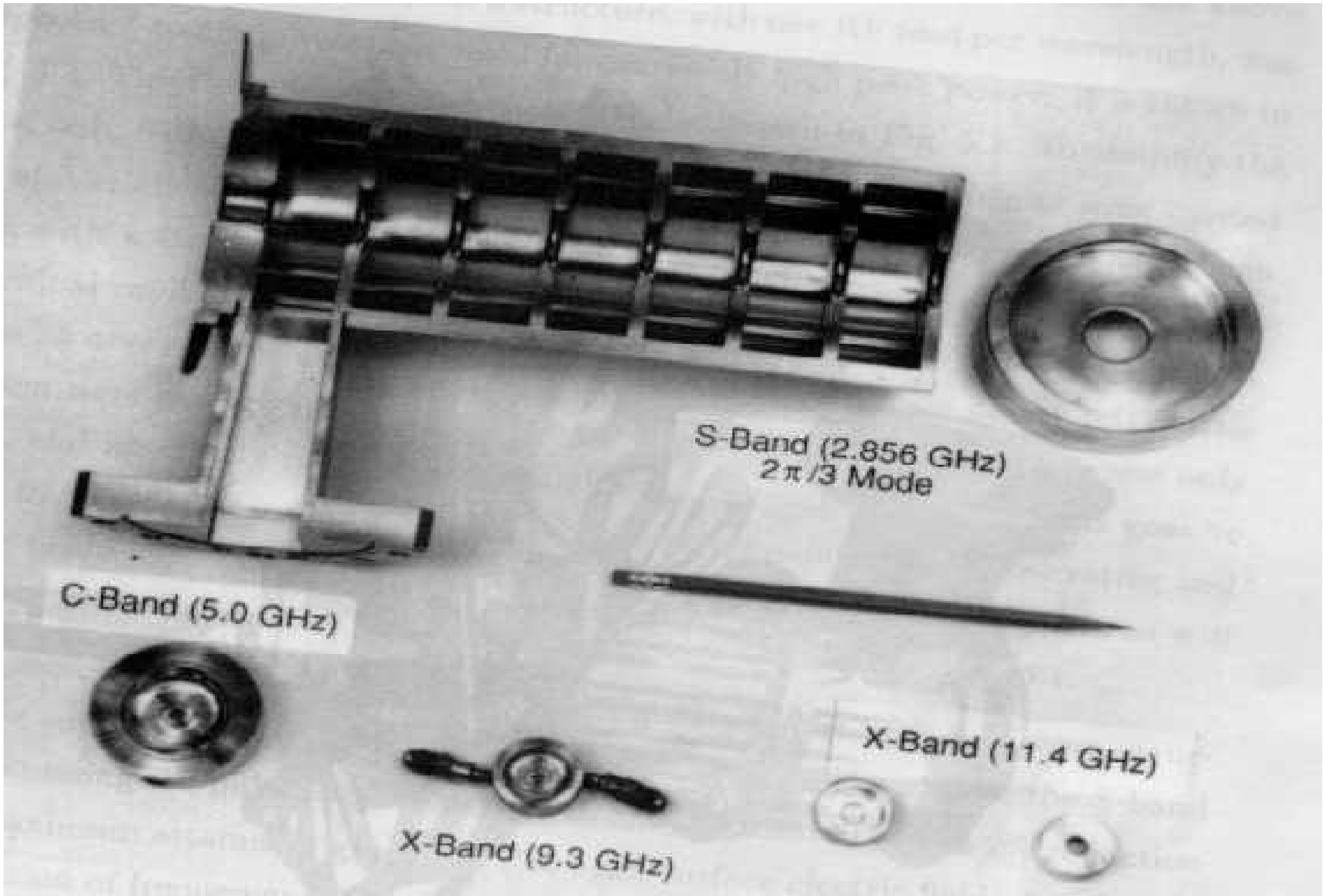

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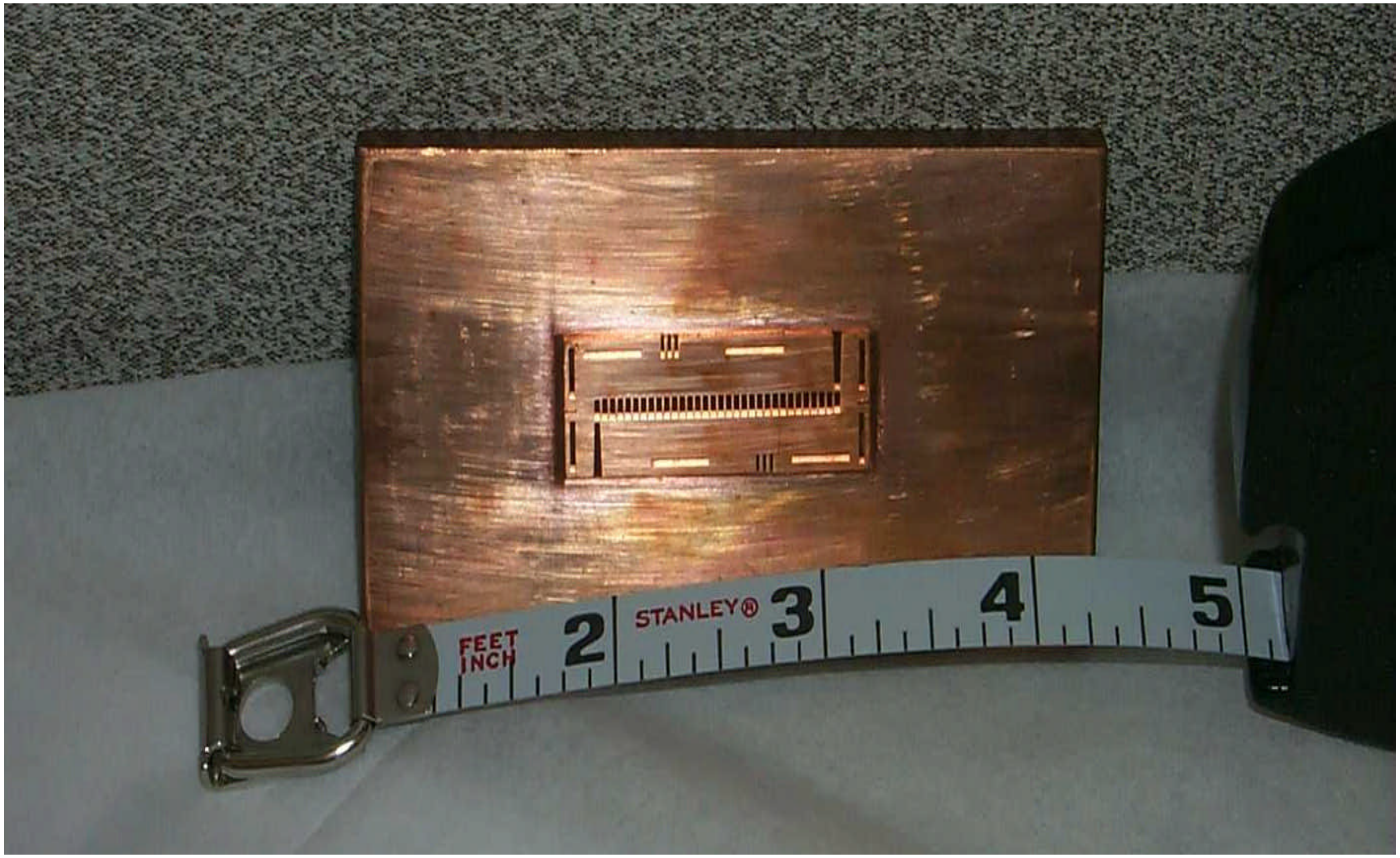

W-Band (94 GHz) Accelerating Structure

Some Basic RF Parameters of Accelerating Structures:

1. The shunt impedance per unit length is a measure of excellence of a structure as an accelerator

$$r_0 = \frac{-E_z^{\ 2}}{dp/dz}$$

Higher shunt impedance is desired since it means more accelerating field for a given spent power.

2. The “unloaded” Q-factor is a measure of the merit of rf cavity as a resonator.

$$Q_0 = \frac{-w\ w}{dp/dz}$$

3. The ratio of r_0 / Q_0 is a very basic parameter in microwave cavities and structures.

$$r_0 / Q_0 = \frac{E^2{}_{0z}}{w \; w}$$

$$w \propto E^2{}_{0z} \times cross\text{-}sectional\,area$$

or

$$w \propto E^2{}_{0z} \times w^{-2}$$

$$r_0 / Q_0 \propto w$$

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4. Group velocity, v_g , is the velocity at which rf energy flows through the accelerator. It strongly depends on the ratio of disk aperture diameter (2a) to cavity diameter (2b):

$$v_g/c \approx K(a/b)^4$$

v_g is an important parameter:

4.1. The fill time, time that is required to fill the accelerator with rf energy depends upon group velocity

$$t_f = l/v_g$$

4.2. The power flow into the structure and the energy stored per unit length of the structure are interrelated to v_g

$$w = P / v_g$$

Since $w \propto E^2_{0z}$, lower value of group velocity is preferred from the point of view of obtaining maximum accelerating fields for a given power flow.

4.3 In general, decreasing v_g, results in increasing r_0 and decreasing Q_0 which results in increasing r_0 / Q_0

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Phase velocity - is the velocity of light (plane wave) in the evacuated waveguide.

$$v_p = {}^{w}\!/_{b} \succ {}^{w}\!/_{k} = {}^{1}\!/_{\sqrt{me}}$$

This is greater than the speed of light at which the particles travel.

Need to *slow down* the phase velocity inside the structure so that it is synchronous with particle velocity.

Voltage Standing-Wave-Ratio VSWR

VSWR is defined as the ratio of $E_{max} : E_{min}$

$$E_{max} = V_i + V_r = V_i\,(1+P)$$

$$E_{min} = V_i - V_r = V_i\,(1-P)$$

$$VSWR,\ S = E_{max} / E_{min} = \frac{1+P}{1-P}$$

If p=0 (matched line), S=1

If p=1 (open or short-circuited line, S = ¥

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Example 1:

A 400 W amplifier is used to drive the input cavity of the linac klystron. Lets assume that for the HV setting of 300 kV and 290 A, a klystron required 120 W to provide 25 MW of rf power. Suppose that input drive power is transmitted down a 50-Ω loss-free line and is terminated at the input cavity of the klystron which presents a 42- Ω load to the generator.

1) what is the reflected power going back to the generator?

2) What is the excitation power into the 1st cavity of the klystron

VSWR, S = $\dfrac{Z_0}{R_L} = \dfrac{50}{42} = 1.19$

Reflection coefficient, $P = \dfrac{S-1}{S+1} = \dfrac{0.19}{2.19} = 0.087$

Reflected Power, $P_r = P^2$ ´ $P_i = (0.087)^2$ ´ $120\ W = 0.90\ W$

Transmitted power to klystron, $P_L = P_i - P_r = 120 - 0.9 = 119.1\ W$

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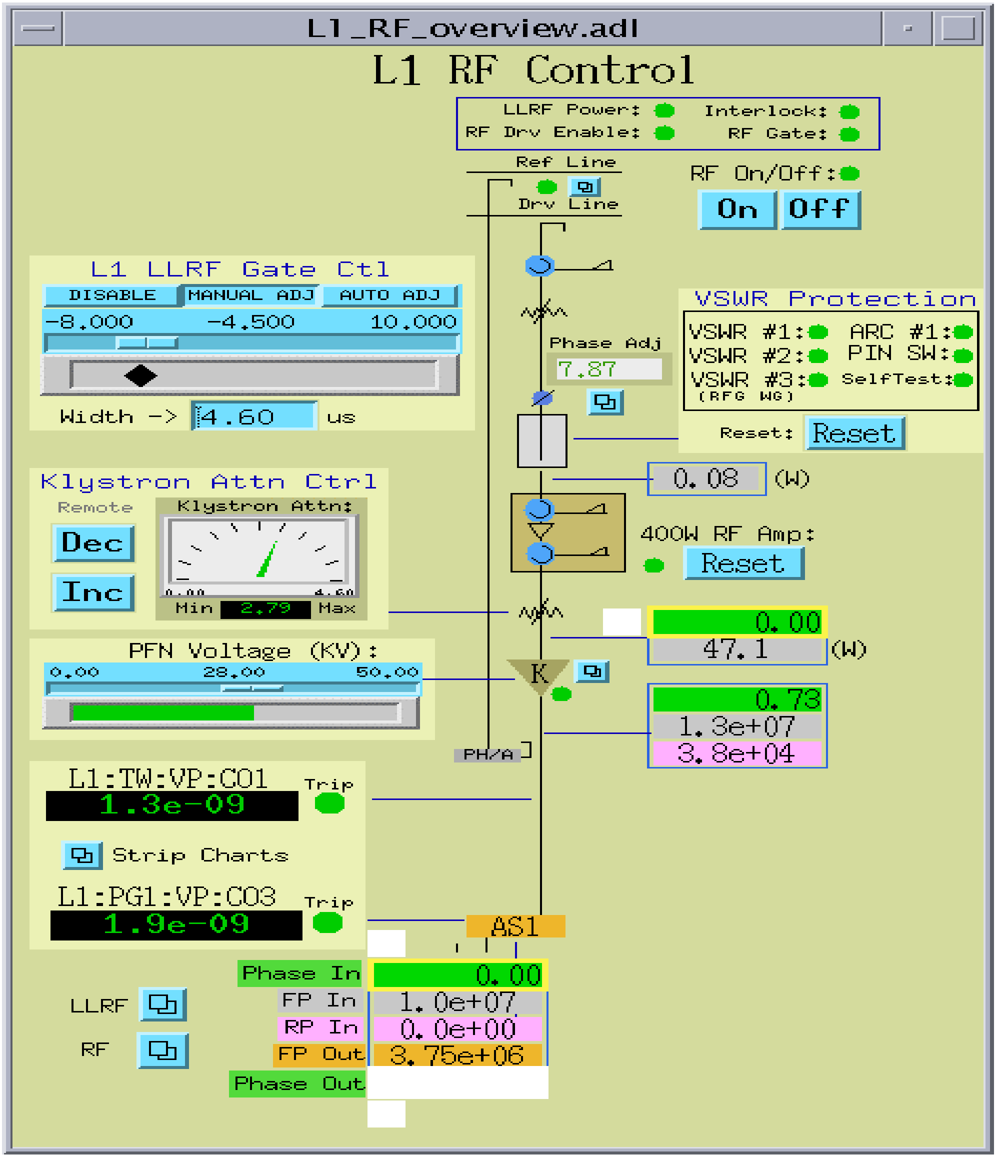

VSWR #1 Klystron

ARC #1 Klystron

VSWR #2 ACS

VSWR #3 RF Gun

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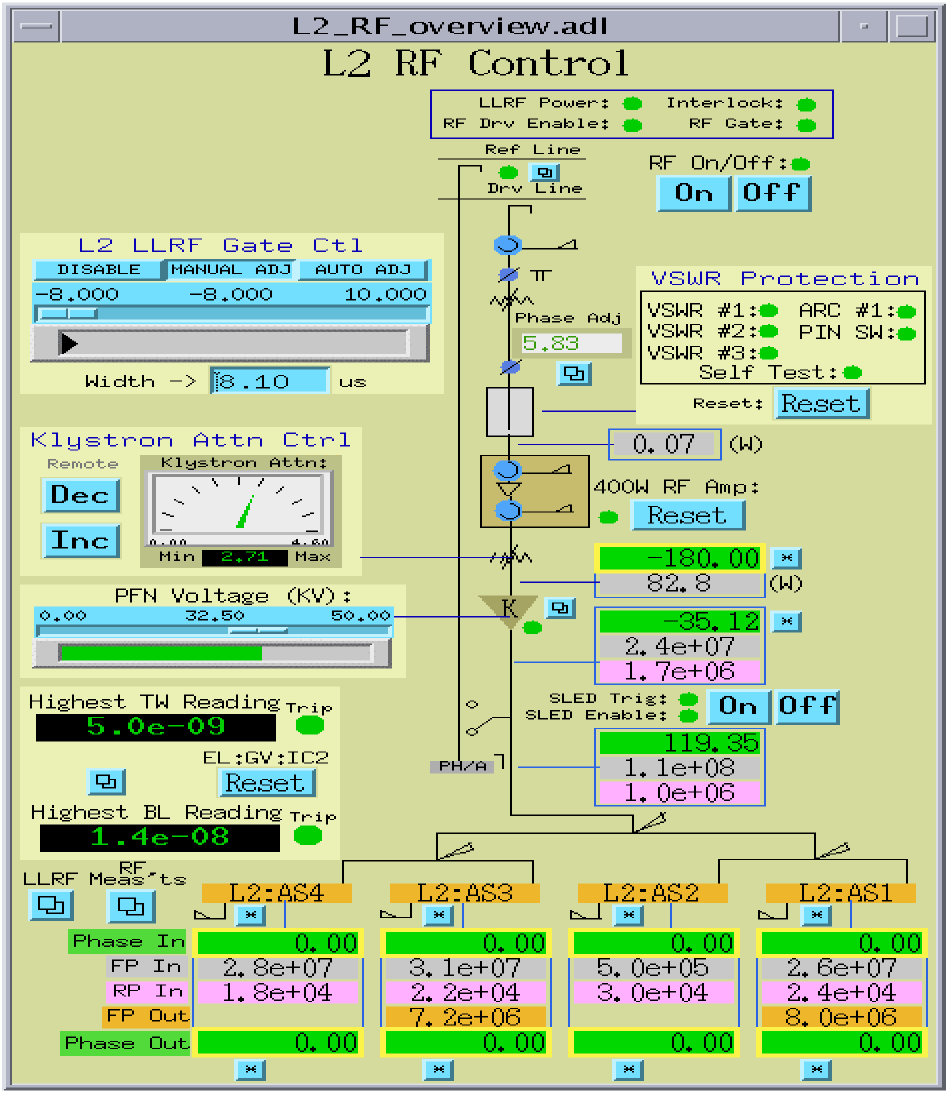

VSWR #1 Klystron

ARC #1 Klystron

VSWR #2 After hybrid split to ACS1 and ACS2

VSWR #3After hybrid split to ACS3 and ACS4

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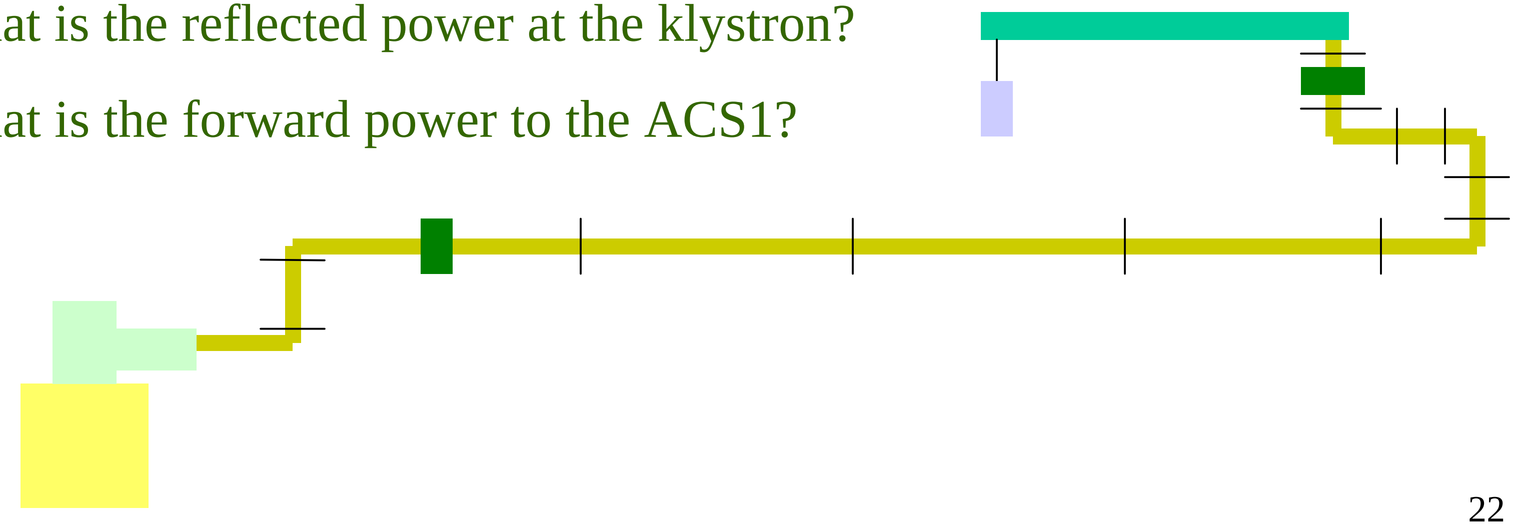
Example 2:

L1 klystron is set to generate 23 MW, measured at the klystron output coupler. The waveguide run from L1 klystron to the input of the ACS1 is roughly 75 feet. Assume that there are two windows in this run, each with a 0.12 dB loss. WR-284 waveguide has a 0.45 dB loss/100 ft. There are 12 flanges in between each with a 0.07 dB loss.

1) what is VSWR for each component?

2) what is the reflected power at the klystron?

3) what is the forward power to the ACS1?



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$$loss(dB) = 20\log_{10} S$$

$Windowloss:$

$$0.12dB = 10\log_{10} S \Rightarrow S = 10^{0.012} = 1.03$$

$Flangeloss:$

$$0.07dB = 10\log_{10} S \Rightarrow S = 10^{0.007} = 1.016$$

$Waveguideloss:$

$$0.45dB \times \frac{75\,ft}{100\,ft} = 0.34dB$$

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$Waveguide:$

$$0.34dB = 10\log_{10} S \Rightarrow S = 10^{0.034} = 1.1$$

$$\text{Total loss}:$$

$$\text{Windows}\,(2) + \text{Flanges}\,(12) + \text{Waveguide}$$

$$0.12dB \times 2 + 0.07db \times 12 + 0.34dB = 1.3dB$$

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$$\text{Total loss } (dB) = 20 \log_{10} \frac{P_t}{P_{inc}}$$

$$-1.3\, dB = 10 \log_{10} \frac{P_t}{P_{inc}}$$

$$P_t = 0.74\, P_{inc} = 0.74 \times 23\, MW = 17\, MW$$

$$P_{refl} = P_{inc} - P_t = 23\, MW - 17\, MW = 6\, MW$$

Reflected power at the klystron window :

$$-1.3\ dB = 10 \log_{10} \frac{P_{r2}}{P_{r1}}$$

$$P_{r2} = .74\, P_{r1} = 0.74 \times 6\, MW = 4.4\, MW$$

$$P_{window} = 6\, MW - 4.4\, MW = 1.6\, MW$$

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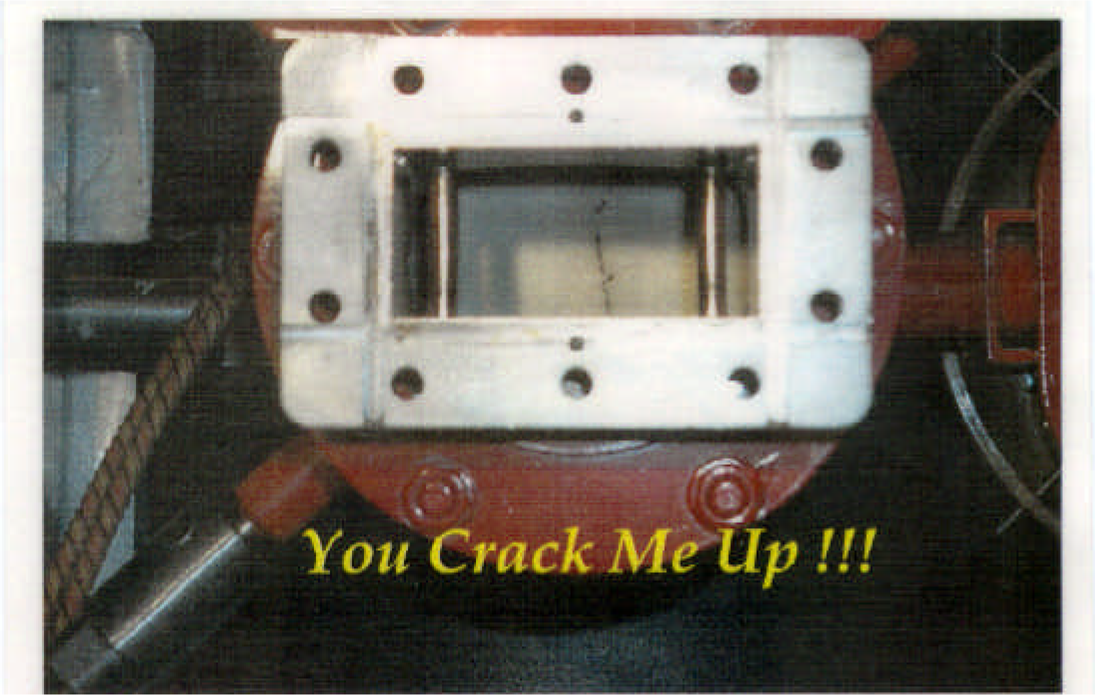

Klystron window crack due to sustained high reflected power

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<u>How does one measure rf power?</u>

- Cannot measure high peak power with any power instruments
- Need to sample a portion of the peak power so a peak power meter can be used without damage
- A waveguide coupler inserted in-line with waveguide is used for this measurement
- Coupling loops are used to sample a small portion of the peak power
- A typical forward loop coupling factor is -56 dB
- For a 30 MW peak power, this corresponds to ~75 W (SAFE)
- Attenuation elements can also be added to reduce the peak power for measurement purposes

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Example 3: A simple "back-of-the-envelop" calculation

L4 klystron is setup with 290 kV and 270 A on the modulator. L4 klystron has an efficiency of 42%. What is the output power of the L4 klystron? What is the output power of the SLED? If the rf pulse length of the driver amplifier is set to 4 μsec, what is the rf pulse length of the SLED output? How long does it take to fill the SLED? What is the power level at each accelerator structure? Assume 7% loss at each power split. If the klystron and the structure are operating at 30 Hz, what is the average power dissipated in the klystron and the structure?

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$$P_{DC} = 290\,kV \times 270\,A = 78.3\,MW$$

$$P_{rf}(kly) = 78.3\,MW \times 0.42 = 32.8\,MW$$

$$P_{rf}(SLED) = 32.8\,MW \times 4.1 = 134.5\,MW$$

$$\text{SLED rf pulse length} \approx 2\,m\,\text{sec}$$

$$t_{fill} = \frac{2Q_0}{(1+b)w} = \frac{2\times 10^5}{6\times p \times 2856 \times 10^6} = 1.86\,m\,\text{sec}$$

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After the first split, output power is 125.1/2 = 62.55 MW. After the second split, output power of each feed is 58.17/2 = 29 MW. So each structure receives ~29 MW rf power.

$$P_{avg}(kly) = 32.8MW \times 30 \text{ pps} \times 4m\text{ sec}$$

$$= 32.8 \times 10^{6} \times 30 \text{ pps} \times 4 \times 10^{-6}\text{ sec}$$

$$\approx 4kW$$

$$P_{avg}(structure) = 29MW \times 30 \text{ pps} \times 2\,m\text{ sec}$$

$$= 1.74kW$$

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Example 4:

RF gun needs approximately 5 MW to provide a beam energy of about 1.6 MeV for injection into the linac. If the output power of L1 klystron is 17 MW, what is the maximum rf power available to each gun?

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$$\frac{P_{out}}{P_{in}} = e^{-2t}$$

$$t = \frac{w\ l}{2 v_g Q}$$

$$v_g / c = 0.0204 \ \text{-}\ 0.0065$$

$$Q = 14{,}000$$

$$l = 3 \text{ meters}$$

$$w = 2p \times 2856 \ MHz$$

$$t \approx 0.48$$

$$P_{out} = 23\ MW \times e^{-2\times 0.48} = 6.5\ MW$$

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Handy Formulas

For a constant-gradient structure:

$$t = \frac{w\, l}{2 v_g(z) Q} = a\, l, a = \frac{w}{2 v_g(z) Q}$$

$$\frac{dP}{dz} = -2a(z) = const = \frac{P_{in}(1 - e^{-2t})}{l}$$

Fill time:

$$t_f = \frac{2Q}{w} t$$

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Example 5: L2 Klystron output power at the input to the SLED is 24 MW. L2 SLED has a power compression factor of 2.6. The electron energy out of rf gun is 1.7 MeV. What is the beam energy at end of L2 sector?

The energy gain E of a charged particle is

$$\mathrm{E} = (2t)^{\frac{1}{2}}[(1 - e^{-t})/t](P_{in} r l)^{\frac{1}{2}}$$

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$r = 54\, M\Omega \,/\, meter$

$Q = 14000$

$t = 0.48$

SLED output power : 24 MW x 4.5 = 108 MW

Structure input power(no loss) : 108 MW ÷ 4 = 27 MW

Assuming 10% loss : structure input power : 24.3 MW

$$E = (2 \times 0.48)^{0.5} \left(\frac{1 - e^{-0.48}}{0.48}\right)(27\, MW \times 54\, M\Omega / m \times 3 m)^{0.5}$$

$E \approx 48\, MeV$ in a 3-meter structure

At the end of L2 : 48 x 4+1.6 MeV = 193.6 MeV